

Search for CP violation at CLEO

David E. Jaffe*, University of California San Diego, La Jolla, CA 92093

Recent results from CLEO on the search for CP violation in beauty and charm meson decays are reviewed.

CP violation (CPV) was first observed nearly 40 years ago in the form of mixing-induced CPV in neutral kaon decays [1]. With the recent confirmation of the observation of direct CP violation in neutral kaon decays [2], only CPV due to the interference between mixing and decay remains to be observed. With the advent of the asymmetric B-factories, this phenomenon may soon be observed with a measurement of $\sin 2\beta$ [3–5]. The latter measurement has the advantage of a nearly unambiguous interpretation in terms of the description of weak decays in the standard model (SM).

CLEO has performed a number of searches for CPV in beauty and charm meson decays. By and large the asymmetries expected in the SM are significantly smaller than the experimental precision so the results are primarily searches for physics beyond the SM.

The CLEO results for B mesons are based upon 9.7×10^6 $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the CLEOII (3.3×10^6 $B\bar{B}$) and CLEOII.V (6.4×10^6 $B\bar{B}$) detector configurations at the CESR symmetric e^+e^- collider. The search for mixing and CPV in neutral charm meson decays utilizes 9.0 fb^{-1} of e^+e^- collisions at $\sqrt{s} \approx 10.6$ GeV accumulated with the CLEOII.V configuration. The inner wire chamber and 3.5 cm radius beampipe of CLEOII [6] were replaced by a 2.0 cm radius beampipe and a three-layer, double-sided silicon vertex detector (SVX) to create CLEOII.V [7]. In addition the argon:ethane gas mixture in the main drift chamber was replaced by a helium:propane mixture. The resulting improvements in momentum and specific ionization (dE/dx) resolution permitted better sepa-

ration of high momentum ($\sim 2.5 \text{ GeV}/c$) charged kaons and pions. The SVX also permits the measurement of the proper decay time of neutral charm mesons that is essential for the study of $D^0\bar{D}^0$ mixing phenomena.

In the B system, CLEO has searched for evidence of direct CPV through the measurements of rate asymmetries in charmless hadronic decays, radiative decays and in $B^\pm \rightarrow \psi^{(\prime)} K^\pm$ decays. Almost all measurements rely on self-tagging decays with the charge of a K^\pm , π^\pm or $K^{*\pm}$ identifying the B or \bar{B} at decay. The branching fractions of a number of charmless hadronic decays observed by CLEO [8,9] are shown in Table 1. Table 1 also contains the preliminary results of the Belle [10] and BaBar [11] experiments confirming the CLEO results.

In the SM charmless hadronic B meson decays occur through $b \rightarrow u$ (“tree”) or $b \rightarrow s$ (“penguin”) transitions. The relatively large rate of $B \rightarrow K\pi$ with respect to $B \rightarrow \pi\pi$ indicates that the amplitudes for the tree (A_T) and penguin (A_P) contributions are comparable. Interference between the $b \rightarrow u$ and $b \rightarrow s$ processes make both the branching fractions ($\propto |A_P/A_T| \cos \gamma \cos \delta$) and rate asymmetries ($\propto |A_P/A_T| \sin \gamma \sin \delta$) sensitive to the weak mixing angle $\gamma \approx \arg(-V_{ub}^*)$. The non- CPV phase difference is δ and is frequently referred to as the “strong” phase. Based on the relative $B \rightarrow K\pi$ and $B \rightarrow \pi\pi$ rates, we have $|A_P/A_T| \sim 1/4$ while measurements of $|V_{cb}|$, $|V_{ub}|$, Δm_d , and ϵ_K indicate that $\gamma \sim 90^\circ$. Thus a large strong phase $|\sin \delta| \sim 1$ could produce rate asymmetries of $\mathcal{O}(50\%)$ that would be observable with the current CLEO data.

CLEO utilizes the unbinned maximum likelihood (ML) method to achieve maximum precision

*Now at Brookhaven National Laboratory, Upton, NY 11973

Table 1

Selected charmless hadronic B branching fractions in units of 10^{-6} . All limits at 90% CL. ♠ = used for CLEO CPV search.

	Final state	CLEO [8,9]	Experiment BELLE [10]	BABAR [11]
♠	$K^\pm \pi^\mp$	$17.2^{+2.5}_{-2.4} \pm 1.2$	$17.4^{+5.1}_{-4.6} \pm 3.4$	$12.5^{+3.0+1.3}_{-2.6-1.7}$
♠	$K^0 \pi^\pm$	$18.2^{+4.6}_{-4.0} \pm 1.6$	$16.6^{+9.8+2.2}_{-7.8-2.4}$	
♠	$K^\pm \pi^0$	$11.6^{+3.0+1.4}_{-2.7-1.3}$	$18.8^{+5.5}_{-4.9} \pm 2.3$	
	$K^0 \pi^0$	$14.6^{+5.9+2.4}_{-5.1-3.3}$	$21.0^{+9.3+2.5}_{-7.8-2.3}$	
	$\pi^\pm \pi^\mp$	$4.3^{+1.6}_{-1.4} \pm 0.5$	$6.3^{+3.9}_{-3.5} \pm 1.6$	$9.3^{+2.6+1.2}_{-2.3-1.4}$
	$\pi^\pm \pi^0$	< 12.7	< 10.1	
	$\pi^0 \pi^0$	< 5.7		
♠	$\eta' K^\pm$	$80^{+10}_{-9} \pm 7$		$62 \pm 18 \pm 8$
♠	$\omega \pi^\pm$	$11.3^{+3.3}_{-2.9} \pm 1.4$		
	ϕK^\pm	$6.4^{+2.5+0.5}_{-2.1-2.0}$	$17.2^{+6.7}_{-5.4} \pm 1.8$	

on the charmless hadronic branching fractions. The ML technique utilizes the observables $\Delta E \equiv E(B) - E_{\text{beam}}$ and $M^2(B) \equiv E_{\text{beam}}^2 - \mathbf{p}^2(B)$ where $E(B)$ and $\mathbf{p}(B)$ are the energy and momentum of the B candidate, respectively, dE/dx , the masses of intermediate resonances and the helicity angle of $B \rightarrow \text{vector, pseudoscalar}$ decays where applicable. In addition event shape variables are combined in a Fisher discriminant that maximizes the separation between the “jetty” $e^+e^- \rightarrow q\bar{q}$ ($q = u, c, s, d$) background and the more spherical $B\bar{B}$ decays. The likelihood is simultaneously maximized for the branching fraction $\mathcal{B} \equiv \frac{1}{2}(\mathcal{B}(\bar{B} \rightarrow \bar{f}) + (\mathcal{B}(B \rightarrow f)))$ and asymmetry $\mathcal{A}_{CP} \equiv (\mathcal{B}(\bar{B} \rightarrow \bar{f}) - (\mathcal{B}(B \rightarrow f)))/(\mathcal{B}(\bar{B} \rightarrow \bar{f}) + (\mathcal{B}(B \rightarrow f)))$ to obtain the results [12] for the five decay modes shown in Figure 1. All measured \mathcal{A}_{CP} are consistent with zero and with the prediction shown indicating that the strong phases are small for these decays. The precision of the measurements varies between 10% and 25% and is entirely dominated by statistics. Systematic checks show that no artificial asymmetries are introduced by either momentum or dE/dx measurements at less than 1% based on studies of kinematically identified K^\pm and π^\pm from D decays.

Radiative B meson decays, in contrast to the charmless hadronic decays, are dominated by $b \rightarrow s\gamma$ transitions in the SM. This situation is quantified by the good agreement between the measured

inclusive rate $\mathcal{B}(b \rightarrow s\gamma)$ [14] and the next-to-leading order calculation [15] as shown in Table 2. Despite this agreement it is possible that non-SM propagators could produce significant asymmetry $\mathcal{O}(40\%)$ in both inclusive and exclusive radiative B decays [16].

The search for CPV in $B \rightarrow K^*\gamma$ decays utilizes the self-tagging $B^+ \rightarrow K^{*+}\gamma$ ($K^{*+} \rightarrow K^0\pi^+, K^+\pi^0$) and $B^0 \rightarrow K^{*0}\gamma$ ($K^{*0} \rightarrow K^+\pi^-$) decays. Only $\sim 60\%$ of the $B^0 \rightarrow K^{*0}\gamma$ candidates are amenable to self-tagging because the kinematic and dE/dx identification of K^{*0} and \bar{K}^{*0} is ambiguous when $|\mathbf{p}_K| \approx |\mathbf{p}_\pi|$. Suppression of backgrounds from $e^+e^- \rightarrow q\bar{q}\gamma$ (initial state radiation) and $e^+e^- \rightarrow \pi^0 X$ is accomplished by requirements on the angle of the γ with respect to the e^+e^- collision axis $|\cos\theta| < 0.71$ and by vetoing γ consistent with a π^0 origin, respectively. Additional suppression of the jetty $q\bar{q}$ background is achieved by requirements on the angle between the γ and the thrust axis [20] of the rest of the event excluding the B candidate. Asymmetries of $\mathcal{A}_{CP} = -0.13 \pm 0.17$ and $+0.38 \pm 0.20$ for the signal and -0.03 ± 0.08 and $+0.06 \pm 0.09$ for the background for neutral and charged $B \rightarrow K^*\gamma$ are determined from fits to the $M(B)$ distributions of B and \bar{B} candidates shown in Figure 2. Assuming that CPV would be independent of the light spectator quark $\mathcal{A}_{CP}(B \rightarrow K^*\gamma) = +0.08 \pm 0.13$ [$+0.01 \pm 0.06$] for the signal [background] where the uncertainty

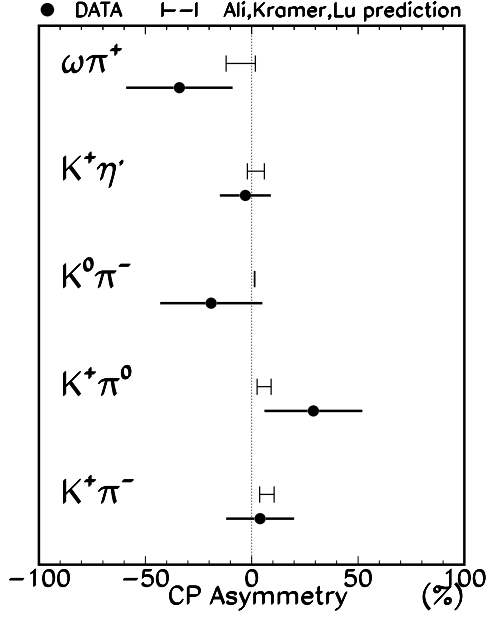


Figure 1. CLEO results [12] for the charge asymmetry for five charmless hadronic B meson decays. The prediction [13] assumes factorization, no soft final state interactions, $\rho = 0.12$ and $\eta = 0.34$.

includes the systematic uncertainty of 2.5% [17].

The techniques used to measure the inclusive $b \rightarrow s\gamma$ branching fraction [14,21] have been adapted to measure $\mathcal{A}_{CP}(b \rightarrow s\gamma)$. The B flavor is determined either by detecting a charged lepton from the semileptonic decay of the other B or by self-tagging through the “pseudo-reconstruction” of X_s ($X_s = K$ and $\leq 4\pi$) with $X_s\gamma$ kinematically consistent with $B \rightarrow X_s\gamma$. The mistag rate for lepton tagging is 0.112 due almost entirely to $B^0\bar{B}^0$ mixing while the mistag rate for the pseudo-reconstruction is either 0.082 or 0.122 depending on the amount and quality of the particle identification information available. The preliminary measured asymmetry for the lepton tag (pseudo-

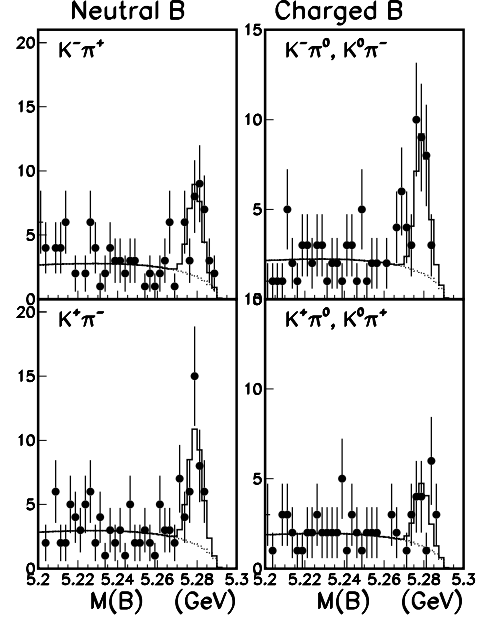


Figure 2. The fitted $M(B)$ distributions for neutral and charged B and \bar{B} candidates for $B \rightarrow K^*\gamma$ decays.

reconstruction) is $\mathcal{A}_{CP} = +0.155 \pm 0.147$ ($\mathcal{A}_{CP} = -0.152 \pm 0.112$) where the uncertainty is statistical only. Studies revealed that asymmetries in lepton, K and π identification and reconstruction are $< 1\%$. Multiplicative uncertainties due to continuum $e^+e^- \rightarrow q\bar{q}$ and $b \rightarrow c$ background subtraction are $\sim 3\%$. The preliminary combined result with all corrections applied is $\mathcal{A}_{CP} = (-0.063 \pm 0.090[s] \pm 0.022[a]) \times (1.00 \pm 0.03[m])$ where s , a and m denote the statistical, additive systematic and multiplicative systematic uncertainties, respectively, or $-0.22 < \mathcal{A}_{CP} < +0.09$ at 90% CL. This limit and the results for exclusive radiative decays exclude a significant fraction of the range allowed by non-SM processes but are still far from the $\mathcal{O}(1\%)$ level predicted by the SM.

Table 2

Measured exclusive and inclusive branching fractions ($\times 10^{-5}$) for radiative B meson decays.

Expt	$B^0 \rightarrow K^{*0}\gamma$	$B^+ \rightarrow K^{*+}\gamma$	$b \rightarrow s\gamma$
Theory [15]			32.8 ± 3.3
CLEO [17,14]	$4.55^{+0.72}_{-0.68} \pm 0.34$	$3.76^{+0.89}_{-0.83} \pm 0.28$	$31.5 \pm 3.5 \pm 3.2 \pm 2.6$
BELLE [18]	$4.94 \pm 0.93^{+0.55}_{-0.52}$	$2.81 \pm 1.20^{+0.55}_{-0.40}$	$33.4 \pm 5.0^{+3.4+2.6}_{-3.7-2.8}$
BABAR [19]	$5.4 \pm 0.8 \pm 0.5$		

The final search for direct CPV is in $B^\pm \rightarrow \psi^{(\prime)}K^\pm$ decays ($\psi^{(\prime)}$ stands for J/ψ and $\psi(2S)$) that proceed by $b \rightarrow c\bar{c}s$. The direct CPV asymmetry for these decays is expected to be very small because the sub-dominant penguin process ($b \rightarrow s\bar{c}$) is suppressed and has nearly the same weak phase $\arg(V_{cb} V_{cs}^* / V_{tb} V_{ts}^*) \approx \lambda^2 \eta + \pi$ ($\lambda = 0.22, \eta \leq 1$) as the dominant process. Non-SM effects could produce a noticeable asymmetry if there is an appreciable strong phase difference between the SM and non-SM amplitudes [22]. The quark process $b \rightarrow c\bar{c}s$ is the same as that for the “golden mode” $B^0 \rightarrow J/\psi K_S^0$ that is being used to measure $\sin 2\beta$. An asymmetry in $B^\pm \rightarrow \psi^{(\prime)}K^\pm$ decays, besides being evidence of non-SM physics, would indicate possible complications for the measurement of $\sin 2\beta$ with $B^0 \rightarrow J/\psi K_S^0$.

Experimentally $B^\pm \rightarrow \psi^{(\prime)}K^\pm$ is nearly as background-free as $B^0 \rightarrow \psi^{(\prime)}K_S^0$. The $\psi^{(\prime)}$ are reconstructed in the $\psi^{(\prime)} \rightarrow \ell^+\ell^-$ ($\ell = e, \mu$) and $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ modes. The charged kaon is identified kinematically to avoid any possible dE/dx -induced bias and $B^\pm \rightarrow \psi^{(\prime)}K^\pm$ candidates are selected by requiring $|\Delta E/\sigma(\Delta E)| < 3$ and $|M(B) - M_{B^+}|/\sigma(M(B)) < 3$ as shown in Figure 3 where $\sigma(x)$ is the candidate-by-candidate uncertainty in x as calculated from the covariance matrices of the reconstructed charged tracks. A small correction of $(+0.3 \pm 0.3)\%$ is applied to the measured asymmetry to take into account the different cross-sections of K^+ and K^- in the CLEO detector material. The asymmetries $\mathcal{A}_{CP}(J/\psi K^\pm) = (+1.8 \pm 4.3 \pm 0.4)\%$ and $\mathcal{A}_{CP}(\psi(2S)K^\pm) = (+2.0 \pm 9.1 \pm 1.0)\%$ are consistent with zero and are currently the most precise measurements of direct CPV in B meson decays [23].

In contrast to B decays, the CLEOII.V SVX

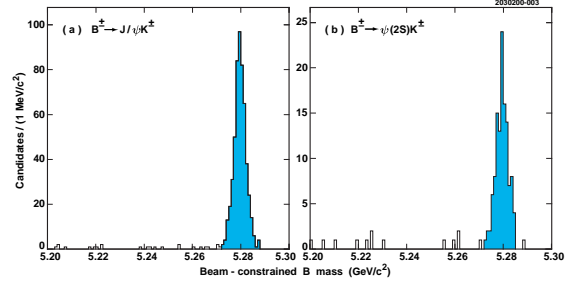


Figure 3. The $M(B)$ distribution of (a) $B^\pm \rightarrow J/\psi K^\pm$ and (b) $B^\pm \rightarrow \psi(2S)K^\pm$ candidates. The shading indicates the candidates selected for the asymmetry measurement.

permits measurement of the proper time dependence of charm meson decays [24] and enables the search for CPV and $D^0\bar{D}^0$ mixing. $D^0\bar{D}^0$ mixing is thought to be both GIM- and Cabibbo-suppressed in the SM although a wide range of predictions exists [25] and recent re-evaluations indicate that the suppression may be only $\mathcal{O}(0.1\%)$ [26,27]. $D^0\bar{D}^0$ mixing through either virtual or real intermediate states is quantified by the dimensionless parameters $x \equiv \Delta m/\Gamma$ and $y \equiv \Delta\Gamma/2\Gamma$, respectively, where Δm and $\Delta\Gamma$ are the mass and width differences of the mass eigenstates and $1/\Gamma$ is the average of the D^0 and \bar{D}^0 lifetimes. Non-SM effects could produce such signatures as $|x| \gg |y|$ and/or large $Im(x)/x$ (CPV). CLEO has searched for $D^0\bar{D}^0$ mixing by comparing the rate of the “wrong sign” (WS) process $D^0 \rightarrow K^+\pi^-$ with that of the “right sign” (RS) $D^0 \rightarrow K^-\pi^+$ decay where the initial D^0 is identified by the charge of the pion in the strong decay $D^{*+} \rightarrow D^0\pi_{slow}^+$. For $|x| \ll 1$ and $|y| \ll 1$,

the proper time dependence of the WS rate is

$$r_{\text{ws}}(t) = (R_D + \sqrt{R_D} y' t + \frac{1}{4} (x'^2 + y'^2) t^2) e^{-t} \quad (1)$$

in units of the D^0 lifetime where R_D is the doubly-Cabibbo suppressed (DCS) rate, $y' \equiv x \sin \delta - y \cos \delta$, $x' \equiv x \cos \delta + y \sin \delta$, and δ is a possible strong phase between the DCS and mixing amplitudes. The observation of a significant quadratic dependence in the proper time dependence of the WS rate would be an indication of mixing through x' or y' while a linear dependence would indicate mixing through y' .

The WS rate is determined from a binned ML fit to the distribution of WS candidates in the Q vs M plane ($M \equiv M(K\pi)$, $Q \equiv M(K\pi\pi_{\text{slow}}^+) - M - M_{\pi^+}$). The shapes of the four distinct backgrounds $e^+e^- \rightarrow q\bar{q}$ ($q = u, s, d$), $q\bar{q} \rightarrow c\bar{c}$, $D^0 \rightarrow \text{pseudoscalar, vector}$ and $\bar{D}^0 \rightarrow K^+\pi^-$ are taken from a simulated event sample corresponding to ten times the data luminosity. The signal shape is taken from the RS data which has measured resolutions of $\sigma(Q) = 190 \pm 6$ keV and $\sigma(M) = 6.4 \pm 0.1$ MeV. The superb Q resolution is possible due to the SVX and is achieved by fitting the π_{slow}^+ to the D^{*+} production point that is taken as the intersection of the beam spot and D^0 pseudotrack. A clear signal is visible in Figure 4 that shows the Q and M projections of the WS candidates when M and Q are required to be within 2σ of the known D^0 mass and D^{*+} energy release, respectively. The proper time distribution of the WS candidates within 2σ of the RS signal region in M and Q is shown in Figure 5 along with a fit incorporating Eqn. 1 with the modifications $R_D \rightarrow R_D(1 \pm A_D)$, $x'[y'] \rightarrow x'[y'](1 \pm A_M)^{\frac{1}{2}}$ and $\delta \rightarrow \delta \pm \phi$ where $+$ $(-)$ corresponds to $D^0(\bar{D}^0)$ for direct CPV , mixing-induced CPV and CPV due to the interference between mixing and decay, respectively. The fit prefers $y' < 0$ (destructive interference) but the mixing parameters y' and x' as well as the three CP violating parameters are all consistent with zero at 95% CL (Table 3) [28].

Preliminary results of a similar analysis for the WS process $D^0 \rightarrow K^+\pi^-\pi^0$ reveal an excess of $N_{WS} = 39^{+10}_{-9} \pm 7$ candidates [9]. Lack of knowledge of the WS resonant substructure (Dalitz plot) confounds the interpretation of this pre-

liminary observation both for the relative WS to RS rate and for the proper time dependence. In essence each point in the Dalitz plot can have a different strong phase δ thus complicating the interpretation via Eqn. 1; nonetheless, a significant $t^2 e^{-t}$ component in the proper time distribution would be evidence for $D^0\bar{D}^0$ mixing.

Finally, CLEO has searched for evidence of direct CPV in the Cabibbo-suppressed processes $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$. The initial D^0 or \bar{D}^0 is tagged by the π_{slow}^\pm from $D^{*\pm}$ decay and the D^0 and \bar{D}^0 rates are extracted from a fit to the Q -distribution with the signal shape taken from Cabibbo-favored $D^0 \rightarrow K^-\pi^+$ decays in data and the background shape taken from simulation. No reconstruction- or detector-induced asymmetry in the π_{slow}^\pm selection, $\mathcal{A}_{CP} = (+0.12 \pm 0.36)\%$, is observed as determined from $K_S^0 \rightarrow \pi^+\pi^-$ decays. No significant CPV is observed $\mathcal{A}_{CP}(KK) = (0.04 \pm 2.18 \pm 0.84)\%$ and $\mathcal{A}_{CP}(\pi\pi) = (1.94 \pm 3.22 \pm 0.84)\%$ (preliminary). The systematic uncertainty from the background shape uncertainty is estimated to be 0.69% and the uncertainty due to π_{slow}^\pm selection is taken as 0.48%.

In summary no evidence for CPV has been observed by CLEO in beauty and charm meson decays with a precision of 4%-25% (beauty) and 2-3% (charm) which is dominated by the statistical uncertainty. Integrated luminosities approximately 100 times that accumulated by CLEO will be needed to attain a statistical precision comparable to the magnitude of direct CPV expected in the SM for beauty and charm decay of $\mathcal{O}(1\%)$ and $\mathcal{O}(0.1\%)$, respectively. The promising turn-on of the B-factories [4,5] indicates that such data samples may be accumulated in approximately five years or less. Such measurements will then need to confront the potentially difficult task of measuring sub-percent detector- and reconstruction-induced asymmetries.

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Table 3

The results of the most general fit to the $D^0 \rightarrow K^+\pi^-$ proper time distribution.

	Central value	95% C.L.
R_D	$(0.48 \pm 0.12 \pm 0.04)\%$	$0.24\% < R_D < 0.71\%$
y'	$(-2.5^{+1.4}_{-1.6} \pm 0.3)\%$	$-5.8\% < y' < 1.0\%$
x'	$(0 \pm 1.5 \pm 0.2)\%$	$ x' < 2.9\%$
$(1/2)x'^2$		$< 0.041\%$
CP violating parameters		
A_M	$0.23^{+0.63}_{-0.80} \pm 0.01$	No Limit
A_D	$-0.01^{+0.16}_{-0.17} \pm 0.01$	$-0.36 < A_D < 0.30$
$\sin \phi$	$0.00 \pm 0.60 \pm 0.01$	No Limit

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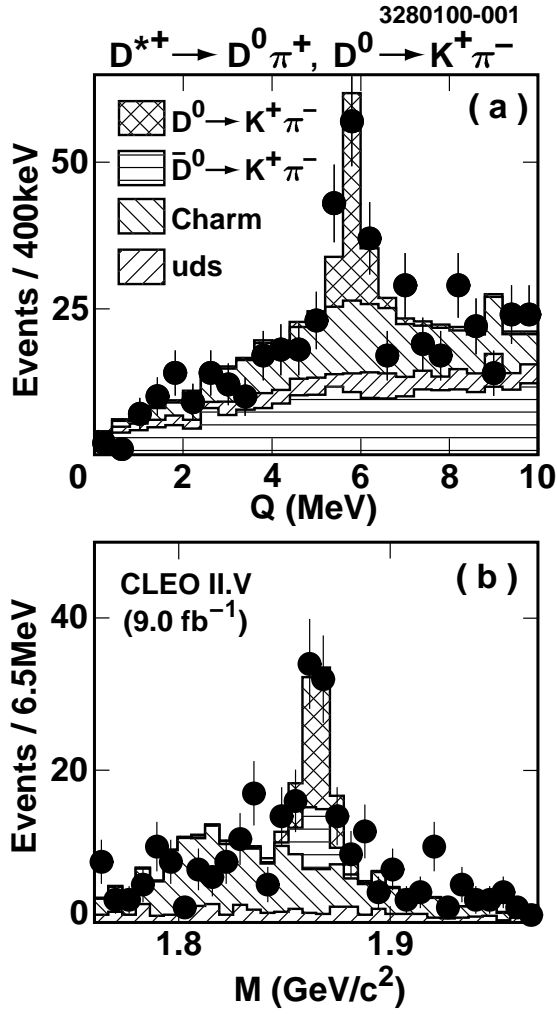


Figure 4. The Q and M data and fit projections for the $D^0 \rightarrow K^+ \pi^-$ candidates.

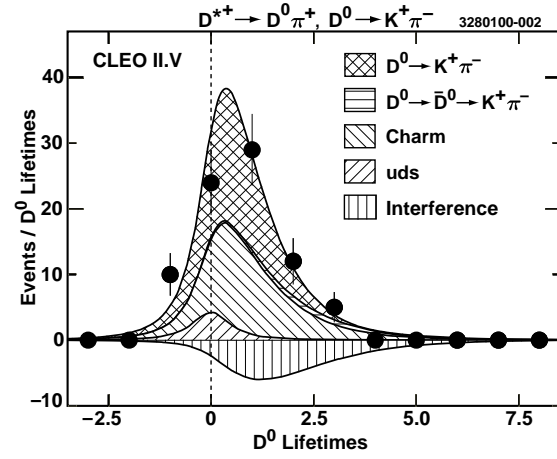


Figure 5. The fitted proper time distribution of $D^0 \rightarrow K^+ \pi^-$ candidates.